Ecological Effects of Vehicular Routes in a Desert Ecosystem

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Introduction

Several recent reviews have summarized the ecological effects of roads (e.g. Forman 1995, Forman and Alexander 1998, Spellerberg and Morrison 1998, Spellerberg 1998, 2002, Forman et al. 2003), including a series of papers in the journal Conservation Biology (2000, Volume 14, Number 1). These reviews universally conclude that construction of roads, the presence of roads in the landscape, and the vehicles that travel upon roads can have a wide range of ecological effects. These effects range from changes in the physical and chemical properties of ecosystems to alterations in the population and community structure of living organisms. These road ecology reviews are important sources of information on the effects of roads, and serve as good general references. However, they understate or do not fully address some very important issues that limit their application to specific situations, such as the development of local land management plans.

One issue that has not been specifically addressed is an integrated understanding of the ecological effects due to both routes created to accommodate vehicular travel, otherwise knows as roads, and routes created by off-road vehicular travel, commonly called off-highway vehicle (OHV) trails. Road ecology reviews by definition focus on roads, and typically do not address the wide range of potential OHV effects which have been studied much less worldwide (but see Webb and Wilshire 1978, 1983, Rowlands 1980). Planning decisions for land management often focus on the nexus between roads and OHV recreation, because they are inextricably inter-related in rural landscapes. This focus is particularly apparent in desert regions where sparse vegetation provides relatively easy access by OHVs to the off-road landscape, much more so than in more vegetated ecosystems where vegetation may create impenetrable barriers to OHV travel.

Repeated OHV use of trails often creates roads which are typically not included in official road databases. In fact, the 6.3 million km of public roads reported in the United States (National Research Council 1997) may be a significant underestimation due to unrecognized roads created by OHVs (Forman et al. 2003). Thus, there is a need for more inclusive evaluations of the relative effects of roads and OHV trails, which we refer to collectively as vehicular routes.

Another poorly understood topic is the relative effects of different types of vehicular routes, each with their own distinctive characteristics. Much of what is known in the general literature regarding the ecological effects of vehicular routes is derived from studies of paved roads, whereas many public land managers primarily manage dirt roads and OHV trails. The characteristics of various types of vehicular routes can vary widely, and these differences may lead to varied ecological effects.

The ecological effects of vehicular routes can also vary among spatial scales, and land managers need to understand these relationships to reliably link their land management actions, which generally occur at local scales, to their land management objectives and goals, which are typically defined at landscape scales. Unfortunately, when managers turn to the technical literature upon which to base their management decisions, they often cannot find studies linking local actions to landscape effects. Scientific studies typically take place at only one spatial scale. On the rare occasion when scientists evaluate both local and landscape processes, the links between scales are often vaguely described. A conceptual framework is needed to compare and contrast the potential ecological effects of different types of vehicular routes at different spatial scales. Managers can then use this framework to more accurately infer the potential effects of their management actions from the result of past studies.

By presenting the full range of possible vehicular route effects, past reviews typically lack the details necessary to evaluate their specific effects within a given ecosystem. For example, habitat fragmentation is often cited as an ecological effect of vehicular routes, but this effect may be more pronounced where routes create major structural gaps in forests than where the contrast between vehicular route corridors and the surrounding landscape is more subtle, such as in shrublands. To be most relevant to land managers, summaries must describe the primary effects of vehicular routes in specific ecosystems.

In this paper we provide a conceptual framework describing the ecological characteristics of various types of vehicular routes, from OHV trails to limited-access highways. We discuss some of the major processes that operate across spatial scales, providing specific examples from the Mojave Desert of western North America. Although this review is most relevant to desert ecosystems, the Mojave Desert in particular, it provides an example of how similar reviews could be done for other ecosystems as well.

Study Region

The Mojave Desert is located approximately between 34 degree N and 37 degree N latitude in western North America, and is transitional between the Great Basin Desert to the north and the Sonoran Desert to the south. It is a semi-arid to arid desert region with highly variable rainfall which can range from virtually zero to as much as 250mm during any given year (Rundel and Gibson 1996). The landscape is characterized by a basin and range topography with elevations that are typically between 600 and 900m. Vegetation is comprised primarily of shrublands and shrub-steppe on deep soils at low and middle elevations, and scattered xeric conifer woodlands on shallow soils at high elevations.

Human disturbances in the Mojave Desert are primarily related to its history of livestock grazing, mining, military training, and other factors associated with its proximity to large human populations in Los Angeles to the southwest and Las Vegas to the northeast (reviewed by Lovich and Bainbridge 1999). Increasing regional human populations in southern California and Nevada, especially since the 1970s, have inevitably led to greater visitation to the Mojave Desert, and the associated increases in the biomass dominance and number of alien invasive plants species, the frequency of wildfires, and the density of vehicular routes. Because vehicular routes facilitate people's access to the landscape, the presence of routes exacerbates all human mediated disturbances. In fact, the intensity of disturbance within and adjacent to vehicular routes, coupled with recurrent disturbance along routes that have high rates of vehicular travel and repeated disturbance from regular route maintenance, make vehicular routes one of the most intense and pervasive forms of anthropogenic disturbance in the Mojave Desert. Accordingly, managing vehicular routes is a current focus of land management planning efforts in this region.

Types of Vehicular Routes

Different types of vehicular routes are distinguished by fundamental characteristics that influence their effects on ecosystems. These characteristics include surface type, presence of shoulders or berms, width of the route corridor, frequency of vehicular travel, density and total area of routes on the landscape, and other factors such as the presence of infrastructure including medians, fences, culverts, and artificial lighting (Table 1). In the following sections we describe the fundamental ways that vehicular routes differ, and discuss their implications for land management.

Table 1. Distinguishing features of major types of vehicular routes.

Route type	Route Corridors Characteristics						
	Surface	Shoulders	Berms	Width	Frequency of travel	Frequency and total area on the landscape	Other factors
OHV trails	Single or two-track dirt	None	None	<1 m-3 m	Low to intermittently moderate	High	Pervasive in wildlands, source of dust, most created since the 1960s, some top soil may be present
Unimproved local roads	1-lane dirt	None	Low	3-4 m	Low	High	Pervasive in wildlands, source of dust, some top soil may be present, perennial plants may be growing in the roadbed
Improved local roads	1 or 2-lane, graded dirt or gravel	None or narrow	Med	5-7 m	Low to moderate	Moderate to high	Source of dust
Collector roads	2-lane, dirt, gravel, or paved	Narrow	High	7-10 m	Moderate	Moderate	
Arterial roads	2-lane paved	Wider	High	30+ m	High	Low	Fencing, culverts, artificial lighting
Limited-access highways	Multi-lane paved	Very wide	High	50+ m	Very high	Very low	Fencing, culverts, median, overpass and interchange structures, artificial lighting

OHV Trails and Unimproved Local Roads

When a vehicle passes across the landscape it leaves a track. Many times these tracks are not driven over again, but sometimes they are, especially if they traverse an obvious path of entry into the landscape (e.g. a wash, Matchett et al. 2004). Repeated tracking eventually creates an enduring trail, which is the most basic form of vehicular route (Fig. 1). Trails created by 2-wheeled motorcycles consist of a single narrow footprint <1m wide. If 4-wheeled vehicles also use these trails, they may widen the footprint to 2-3 m creating a two-track jeep trail (Fig. 1). In areas of very frequent OHV use, such as OHV "pit" or staging areas, or in areas of intensive military ground training, multiple routes may merge into very broad areas devoid of perennial vegetation 10 to 100 m or more across. Although these areas represent highly intense and focused surface disturbance, they only comprise a fraction of the total area encompassed by the less intensively disturbed but more extensive networks of OHV trails in the Mojave Desert.

Once a highly visible trail is created, it becomes more susceptible to regular use, and at some point may widen even further and become recognized as an unimproved local road. Rather than try to define the specific point at which an OHV trail becomes an unimproved road, we consider these two types of routes as components of overall OHV route networks. Land managers commonly view their travel management programs in this way, and we think they should be presented in a similar integrated fashion in literature reviews and other decision-support tools.

Off-highway vehicle trails and unimproved local roads are typically <4m wide with a dirt surface (Fig. 1, Table 1). By definition, they have never been bladed, filled, or otherwise improved, so they do not possess many of the ecologically significant characteristics of more developed roads, such as large widths, berms, or shoulders (Table 1). Berms along the midline of unimproved local roads may develop over time, especially on roads that have evolved from two-track jeep trails. Some top-soil may still be in place and emergent perennial

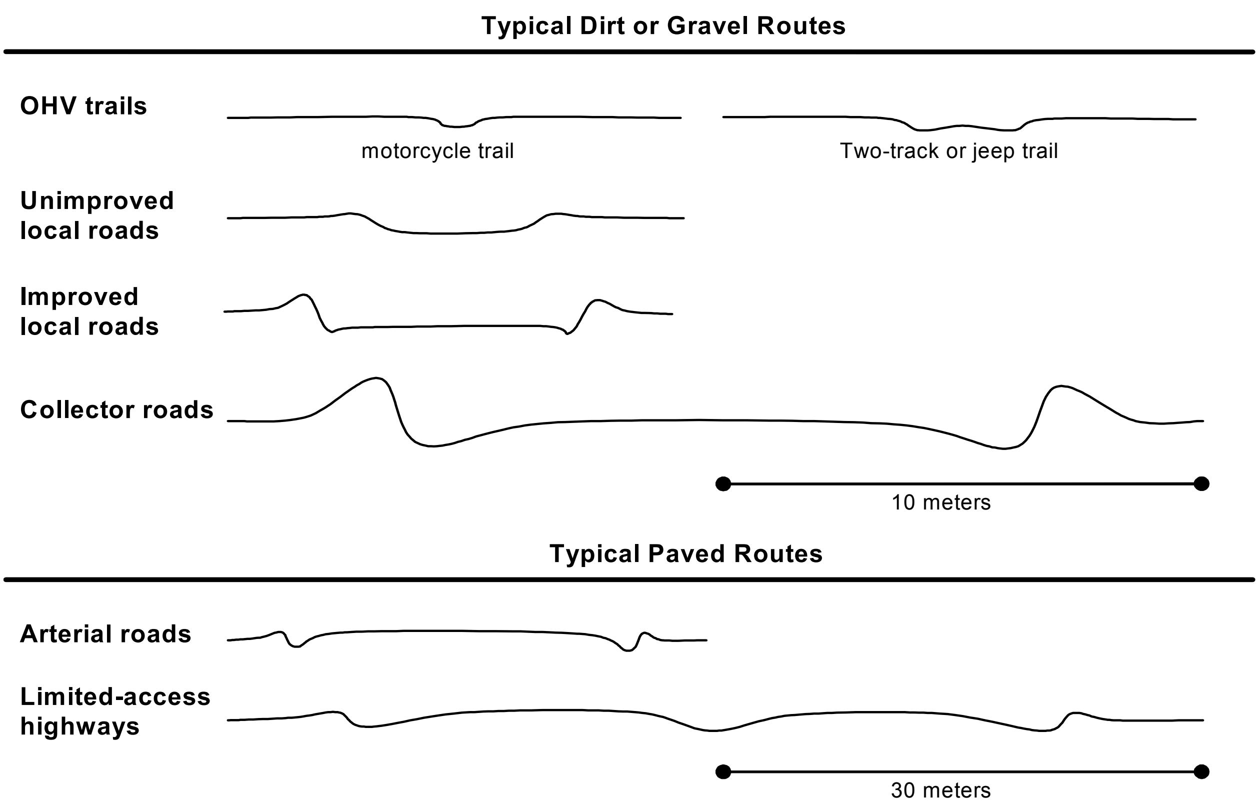

Figure 1. Generalized cross-sectional profiles of each type of vehicular route.

shrubs and grasses may grow up within the roadbed, especially along midline berms. Frequency of travel is typically low on OHV trails and unimproved local roads, except on holiday weekends or during OHV races when use can increase dramatically, and in the vicinity of designated OHV Open Riding Areas where vehicle travel is not restricted to specific routes. Individually, OHV trails and unimproved local roads may lack broadscale ecological impacts, but collectively they represent a significant threat when trails are dense and comprise a large portion of Mojave Desert landscapes (Matchett et al. 2004).

In the past, land managers typically did not plan or direct the establishment of OHV trails or unimproved local roads. These routes may have developed and continue to develop in areas that cannot sustain their long-term persistence as functioning vehicular routes. For example, routes straight up hillsides (e.g. hill climbs) facilitate the downslope flow of water and promote rills and gullies that ultimately impede vehicular travel. This process in turn leads to multiple redundant routes that characterize heavily used hillslopes (Wilshire 1978).

OHV trails may be poorly signed in some places, causing OHV riders to inadvertently leave a designated trail and create new ones. Thus, the presence of OHV trails can lead to the development of new routes (Goodlett and Goodlett 1993) that result in trail networks with high densities until individual routes become indistinguishable from one another (Matchett et al. 2004). In contrast to OHV trails, unimproved local roads are clearly distinguishable when traveling across the landscape in a vehicle, and there is less chance that vehicle operators inadvertently lose their way and travel off these routes. However, these routes often lack the benefits of civil engineering and become eroded or otherwise degraded over time. Route degradation can then promote detours as people drive around the degraded stretches, and these detours may eventually become parallel redundant routes.

Most OHV trails in the Mojave Desert are probably less than 40 years old, since OHV recreation first became popular during the late 1960s (Bureau of Land Management 1980, and subsequent amendments). Old trails may become abandoned over time, but the number of new trails created can exceed those previously abandoned, resulting in a net increase over time in some parts of the Mojave Desert (Matchett et al. 2004). Unimproved local roads can be much older, since they often developed in response to historical needs for access to the landscape for mining, livestock operations, and maintenance of wildlife guzzlers.

Improved Local Roads and Collector Roads

These vehicular routes represent a significant step up in ecological effects. They are typically bladed, which removes topsoil and creates berms and shoulders (Fig. 1, Table 1). They are wider than unimproved local roads and OHV trails, and may have fill, gravel, or asphalt added to create a more stable road surface. These additions can cause physical and chemical changes in soil properties. Although frequency of travel on improved local roads and collector roads is higher, frequency of improved roads in the landscape and total area covered by them is lower than that of unimproved local roads and OHV trails.

Arterial Roads and Limited Access Highways

In contrast to the previously discussed types of vehicular routes that primarily provide access to landscapes within a region, arterial roads and limited-access highways facilitate long-distance travel between regions. The most extreme examples of roadbed and shoulder width and engineered surfaces characterize these vehicular routes (Fig. 1, Table 1). They also possess features rarely found in other types of routes, including fenced right-of-ways, medians, culverts, and overpass and interchange structures. Frequency of travel and vehicle speed are the highest among route types, but their frequency of occurrence on the landscape and area covered are the lowest of all types of vehicular routes in rural areas.

Spatial Scales of Vehicular Route Effects

The ecological effects of vehicular routes can be characterized at three spatial scales: (1) direct effects within route corridors (2) indirect effects distributed along gradients radiating outward from route corridors; and (3) dispersed landscape effects resulting from the cumulative effects of multiple routes across landscapes (Fig. 2). Ecological effects at each spatial scale are not mutually exclusive, as the cumulative influence of smaller-scale local effects associated with individual routes typically translate into larger-scale landscape effects resulting from the net influence of multiple routes. To be most useful to land managers, information on the effects of vehicular routes should be presented in the spatial context at which ecosystem processes or human use patterns occur, and the links between spatial scales should be explicitly described.

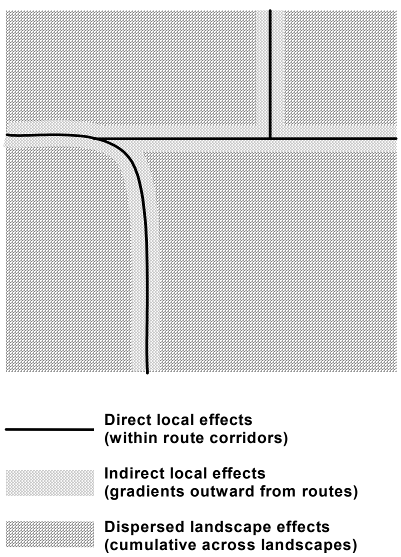

Figure 2. Three spatial scales of vehicular route effects.

Direct effects occur within the footprint of vehicular routes, including other features that may be created through their continued maintenance (e.g. medians, shoulders, or berms). We call this area the vehicular route corridor (sensu "road corridor" Forman and Alexander 1998). Initial effects associated with the creation of routes are obvious and dramatic, including alteration of soils and direct mortality of vegetation and wildlife. Ongoing repeated effects are associated with patterns of vehicular use (e.g. vehicle types, rates of speed, frequency of use) and the continued maintenance of the route (e.g. blading or spraying herbicides along shoulders). Direct effects vary among different types of vehicular routes, with the most severe occurring along paved highways and the least severe occurring along OHV trails.

Although direct effects are relatively consistent across ecosystems, their interactions with the unique characteristics of individual ecosystems dictate how they translate into the indirect and dispersed landscape effects which are of primary concern for land managers. For example, direct effects of vehicle routes on soil moisture will likely have greater ecological effects in arid compared to more mesic ecosystems, because water is more limiting to primary productivity in the former than in the latter.

Indirect effects influence areas immediately adjacent to vehicular routes, otherwise known as the route-effect zone (sensu "road-effect zone" Forman and Alexander 1998). The width of this zone varies greatly among different types of vehicular routes. Characteristics of this zone may also be influenced by ecological gradients along the length of vehicular route corridors (e.g. Forman and Deblinger 2000), the variable responses of different ecological factors to vehicular routes (Forman et al. 2003), or the unique properties of different types of vehicular routes. Thus, definitions of route-effect zones should be tailored for specific types of ecosystems, ecological response factors, and vehicular routes, and may not be accurate beyond the context in which they were developed.

Dispersed landscape effects of vehicular routes can be very difficult to determine in a landscape of multiple land uses, such as in the Mojave Desert. In addition, even when a significant correlation is established between route densities of various types and environmental response variables, the primary causes for this relationship can be difficult to identify (e.g. Brooks et al. in prep.). Interactions among the effects of various types of vehicular routes, the effects of other land use disturbances, and the characteristics of specific ecosystems, all influence the net effect on environmental response variables. As a result, dispersed landscape effects are also context-specific, and should be generalized very cautiously.

Effects of Vehicular Routes on Soils in the Mojave Desert

Vehicular routes can directly affect soils by removing them, adding to them, changing their physical and chemical composition, or covering them with gravel or asphalt. Many of these changes have effects that extend beyond the route corridor, and contribute to indirect and dispersed landscape effects on plants and animals.

One of the most significant ecological effects that vehicular routes have on soils in desert regions involves changes in water runoff patterns. Vehicular routes that run straight up hillslopes can promote soil erosion and the development of rills and gullies as mentioned earlier in this paper. This most often occurs with OHV trails and unimproved dirt roads. Sediment yield during rainfall events can be 10- to 20-fold higher on Mojave Desert hillslopes following OHV use (Iverson 1980). In Dove Springs Canyon in the western Mojave Desert, 0.3m of soil eroded downslope along OHV "hill-climb" trails between 1973 and 1975 (Snyder et al. 1976). OHV use accelerates water erosion on hillslopes by decreasing soil infiltration rates, loosening soil surfaces, channelizing run-off in vehicular tracks, and reducing microtopographic roughness oriented perpendicularly to the slope (Iverson 1980).

Vehicular routes that run parallel to elevation contours can also alter runoff patterns by redirecting water along roadside ditches to low points along the road, after which water continues on downslope in a more concentrated stream than otherwise would have occurred. This process concentrates channels at higher slope positions (Montgomery 1994), resulting in more elongated first-order drainage basins, and accelerated rates of soil erosion (Forman and Alexander 1998). These effects become more pronounced as the route corridor becomes more impervious to surface flow, such as along raised roadbeds or where diversion berms or "chevrons" have been constructed upslope of paved highways. These effects may also increase as the impermeability of the soil and the size of the watersheds feeding each culvert increase. The result is a significant redistribution of soil moisture, increasing on the upslope side of vehicular routes and along the channels that flow from culverts on the downslope side, and decreasing on the upland areas between these downslope channels. This can have significant repercussions for plants as we discuss in the next section.

Heavily traveled routes can produce significant amounts of air pollution that create gradients of heavy metal in the soil and plants within 20 to 200m from route corridors (Trombulak and Frissell 2000). Bioaccumulation of heavy metals in animals that eat affected plants is a significant concern, especially when increased levels reduce life spans and reproductive rates. The desert tortoise (Gopherus agassizii) is a federally threatened species that has declined in numbers during recent years due to increased incidence of respiratory tract and shell diseases. Increased levels of heavy metals along roadside may facilitate the contraction of these diseases (K. Berry, pers. comm.).

High rates of vehicular travel may also be positively correlated with NOx pollution and increased levels of N in the soil. Increased soil N affected plant communities up to 200m from a highway in Britain (Angold 1997). Experiments in the Mojave Desert suggest that increased soil N can promote the growth of non-native annual plants, and reduce growth and diversity of native annual plants (Brooks 2003, E. Allen unpublished data).

Vehicular routes with dirt surfaces can also be a significant source of dust. OHV recreation in particular has been identified as the cause of dust plumes covering areas as large as 1,700km2 (Nakata et al. 1976).

Effects of Vehicular Routes on Vegetation in the Mojave Desert

Vegetation cover and productivity can significantly increase along vehicular routes with paved (Johnson et al. 1975, Vasek et al. 1975, Lightfoot and Whitford 1991) and dirt (Johnson et al. 1975, Vasek et al. 1975, Hessing and Johnson 1982, Starr and Mefford 2002) surfaces. This effect has been attributed to either release from competition from nearby plants removed along the road corridor, enhancement of soil moisture from rainfall flowing off the road surface to the base of the berm facing the roadside, or enhancement of rainfall flowing off of the upslope landscape to the base of the berm facing the surrounding desert (Johnson et al. 1975, Vasek et al. 1975). The latter two hypotheses are supported by observations of effects where berms were present, and did not occur where berms were absent along improved dirt roads (Starr and Mefford 2002). However, Vasek et al. (1975) observed that enhancement of plant productivity along dirt roads can also occur where obvious drainage factors do not apply. Johnson et al. (1975) suggested that water running off road surfaces affects plant productivity because the roots from shrubs on roadside berms tend to grow towards the roadside, and that upslope runoff from the surrounding desert is important since productivity can be much higher on the upslope than on the downslope side of paved roads. In general, plant productivity does not seem to increase along OHV trails (M. Brooks personal observation), is greater along paved than dirt roads, but does not significantly scale up proportionately to road width from smaller paved roads to limited-access highways (Johnson et al. 1975).

Vehicular routes are also a primary pathway for plant invasions into arid and semi-arid ecosystems (Johnson et al. 1975, Amor and Stephens 1976, Brooks and Pyke 2001, Gelbard and Belnap 2003). Vehicles serve as dispersal vectors for alien plant propagules (Clifford 1959, Schmidt 1989, Lonsdale and Lane 1994), and disturbances within vehicular route corridors facilitate establishment of invading ruderal plants (Greenberg et al. 1997). Single passes by OHVs create tracks that can provide favorable microsites for annual species in the deserts of Kuwait (Brown and Schoknecht 2001), and for the aliens Schismus barbatus and Erodium cicutarium in the Mojave Desert (Davidson and Fox 1974). Annual plant invaders commonly occur in high amounts on berms along most paved, and some improved dirt roads in the Mojave Desert (M. Brooks pers. obs.). In the Colorado Plateau, northeast of the Mojave Desert, cover of the invasive grass Bromus tectorum was three times higher along verges of paved roads compared to two-track jeep trails, and compared to cover of five common exotic forbs on verges of paved roads as well (Gelbard and Belnap 2003). Total exotic cover and species richness were both over 50% higher in the route-effect zone 50m from paved compared to two-track routes. In the Mojave Desert, species richness of annual plants was higher along roadsides, especially along paved roads, and most of this difference was attributed to the non-natives Erodium cicutarium, Schismus barbatus, and Bromus rubens, and the ruderal natives, Amsinckia tesselata and Descurainia pinnata (Johnson et al. 1975). There is also evidence that these indirect effects of vehicular routes may translate into dispersed landscape effects, since alien species richness and biomass of the alien forb Erodium cicutarium were positively correlated with density of dirt roads within 1 square mile areas in the Mojave Desert (Brooks and Berry accepted).

The typical pattern of plant invasions into the Mojave Desert traces the following course. In the first phase, new invaders appear along roadsides near their adjacent regions of origin. For example, the invasive mustard Brassica tournefortii spread northward along paved highways into the southern Mojave Desert from its initial point of colonization in the Sonoran Desert (Minnich and Sanders 2000), then on through to the northern Mojave Desert and into the Colorado Plateau (M. Brooks pers. obs.). In some cases invaders may "island hop" into the region by establishing first in urbanized or agricultural regions within the Mojave Desert, then move outward along roadsides into less developed areas. Once within the region, invaders are pre-positioned to begin the second phase of invasion, the spread away from roadsides into wildland areas. The initial stages of spread away from vehicular routes occurs within landscape features (e.g. washes or north facing hillslopes) or microsites (e.g. beneath perennial shrubs) where soil moisture levels are locally high (M. Brooks unpub. data). Disturbed areas adjacent to roadsides are also more readily invaded, such as utility corridors (M. Brooks pers. obs.), areas with high levels of OHV use (Davidson and Fox 1974, Brooks et al. in prep), or burned areas (M. Brooks pers. obs. Milberg and Lamont 1995). The third and final stage of invasion, which is achieved by relatively few species in the Mojave Desert (Brooks and Esque 2002, Brooks and Berry accepted), is the naturalization of invader populations in wildland areas away from roads.

Effects of Vehicular Routes on Animals in the Mojave Desert

Animals are directly affected by habitat loss associated with the development of vehicular routes, and by mortalities caused by collisions with vehicles traveling on these routes. Studies of the federally listed desert tortoise indicate that population densities are lower near vehicular routes (Nicholson 1978, Berry and Turner 1984, Boarman et al. 1997). Fenced exclusion of ground-dwelling vertebrates from a limited-access highway in the western Mojave Desert reduced road kills of desert tortoises by 93%, and of vertebrates in general by 88% (Boarman and Sazaki 1996). However, another study from a limited-access highway in the northern Mojave Desert suggests that rodents rarely crossed the highway (Garland and Bradley 1984). Thus, generalizations about the direct effects of vehicular routes on rates of animal mortality are difficult to make, because responses may vary among route types, and among taxa with differing behavioral characteristics and habitat preferences.

Enhanced productivity of vegetation along improved roads, especially those that are paved, can lead to increased abundances of insects (Lightfoot and Whitford 1991) and rodents (Garland and Bradley 1984). However, these two studies do not span more than one year of sampling, and road effects can vary among years of contrasting rainfall. For example, densities of antelope ground squirrels (Ammospermophilus leucurus) in the western Mojave Desert gradually increased from >200m, to 100 to 200m, to 0 to 100m from improved dirt roads during two years of low rainfall, whereas the trend reversed during an intervening year of high rainfall (Starr 2001). The explanation was that animals are drawn to areas near roads during years of low rainfall because their annual plant forage is more abundant there compared to areas further from roads. During years of high rainfall, forage is abundant across the landscape and is not the limiting factor it is during years of low rainfall. The negative relationship of ground squirrels with roads when rainfall is high indicates there may be other negative factors associated with roads that are either only manifested during years of high rainfall, or are masked by the positive influence of greater forage availability close to roads during years of low rainfall.

Increased vegetation structure along improved roads may also increase the diversity of bird communities. However, one study that evaluated the general relationships between vegetation structure and bird community diversity in the Mojave Desert did not find significant correlations (Brooks 1999). The apparent increase in habitat quality along road verges may have a net negative effect as animals are drawn from the surrounding desert towards roadsides where they are more likely to be killed by passing vehicles, or may bioaccumulate harmful heavy metals concentrated in their forage plants.

A basic question relates to how the direct and indirect local effects of vehicular routes translate into dispersed effects on animal populations and communities across the landscape, and how these effects vary a rainfall fluctuates from year to year. In particular, studies are needed to determine the characteristics of vehicular routes that create barriers or filters to animal movement patterns and lead to habitat fragmentation for animals. No studies that we know of have directly evaluated the role of vehicular routes in fragmenting wildlife habitat in the Mojave Desert.

Summary of Existing Research

Most of what is known regarding the ecological effects of vehicular routes in the Mojave Desert is focused on OHV networks of trails and unimproved local roads (40 of 50 studies) (Appendix A). These studies provide important insights for inferring the potential ecological effects of other types of vehicular routes. All of the studies on vehicular routes addressed some aspect of direct effects: 5 addressed indirect effects and 5 addressed dispersed effects. Very few addressed multiple scales: 5 direct plus indirect, 4 direct plus dispersed, and none addressed all three scales.

Most studies have quantified direct effects of vehicular routes by comparing conditions within the road corridor with reference conditions at a single distance outside of the corridor. These studies can produce misleading information if the reference site lies within the indirect route-effect zone, thus not serving as true controls. Studies focused on the local effects of individual routes should be designed to evaluate both direct and indirect effects, and incorporate a gradient of sites at various distances from the route. Gradient study designs offer an effective way to evaluate the local effects of vehicular routes, because they can identify inflection points and asymptotes of ecological responses to routes. True controls can then be defined as the area beyond the distance at which the gradient effect reaches its asymptote. Gradient data can also be used to develop transfer functions for modeling the dispersed landscape effects of multiple routes, an effect essential to include in land management plans.

Most studies (44 of 50) evaluated creosotebush scrub habitat, whereas only 8 evaluated shadscale scrub, 3 joshua tree woodland, 4 saltbush scrub, 4 desert sand dunes, 2 blackbrush scrub, 1 microphyll woodland, and 4 were not specific to a particular vegetation type (Appendix A). Creosotebush scrub is the dominant vegetation type in the Mojave Desert (Rundel and Gibson 1996), but saltbush scrub, blackbrush scrub, and Joshua tree woodland also cover a considerable portion of the region, and probably need to be included in vehicular route studies proportionally more than they have been. Pinyon-juniper woodland has not been studied at all, although it is of concern to land managers because it occurs in relatively small and disjunct stands that may be especially vulnerable to landscape disturbances such as those stemming from vehicular routes.

Soils were included as a response variable in almost half of the studies (24 of 50), but all but 2 of these studies focused exclusively on OHV trails or unimproved local roads (Appendix A). Similarly, of the 11 annual plant studies, all but 3 were focused on OHVs and unimproved local roads. Thus, what is known about soil and annual plant responses to vehicular routes in the Mojave Desert is mostly derived from studies that are focused on OHV effects and at local scales. In contrast, the 30 studies that addressed perennial plants and the 13 that addressed animals, were more equally distributed among vehicular route types. Few studies addressed multiple combinations of soil, annual plant, perennial plant, and animal response variable categories: 16 addressed some combination of two categories, 6 addressed combinations of three, and none simultaneously addressed all four.

Future research should evaluate multiple scales, including direct, indirect, and diffuse effects of vehicular routes. Understudied vegetation types should be evaluated to improve the breadth of knowledge across different ecological conditions within the Mojave Desert. The generality of responses of soils and annual plants to OHV trails and unimproved local roads needs to be tested in response to other types of vehicular routes. Studies that integrate multiple combinations of soils, annual plants, perennial plants, and animals would also help address management questions regarding the effects of vehicular routes on higher order ecosystem responses such as wildlife populations and communities.

Management Implications

The current decision process of route designation in the Mojave Desert is site specific, and relies to various degrees on biological, cultural, and recreational information. For example, if a route passes through high priority habitat for sensitive species, or provides access to sensitive cultural sites, then the route may be considered undesirable and targeted for closure. However, if the route provides access to recreation areas, then it may be deemed desirable and targeted for possible designation as an open route. Effects of routes on physical processes (e.g. dust production or soil erosion) are rarely considered. Final decisions must balance different aspects of resource protection with other land uses, and the decision process needs to be supported by as much objective science as possible for decisions withstand intense scrutiny.

The biggest challenge to public land management is developing objective criteria upon which route designation decisions can be made, and later justified. Another challenge is selecting and defining indicators for successful management, that is, being able to determine when management actions produce their desired results. High-priority information needs often expressed by land managers include the need to understand the effects of vehicular routes on plant invasions, native animal populations, and local biotic communities (M. Brooks pers. obs.).

Key questions also include: What characteristics of route networks most effectively promote plant invasions? What feature of route networks result in significant habitat fragmentation for animals? Which effects animals more, the type of vehicular activity that occurs on a route or the characteristics of the route itself? How do indirect and dispersed landscape effects differ among types of vehicular routes? Are there signals to indicate when effects at smaller scales will lead to effects at larger scales? How do the effects of vehicular routes compare to the effects of other land uses and landscape disturbances?

In conclusion, effective science products should address thresholds of ecological responses to roads, and thresholds of ecological recovery from past road effects following restoration efforts, and translate directly into criteria for route designation. Ideally, these criteria should provide land managers with an early-warning system to determine when and where the effects of vehicular route will cause the biggest ecological problems. This information could be used to prioritize management actions related to vehicular routes among the multitude of land use issues that public land management agencies must deal with.

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Appendix A. Published studies evaluating ecological effects of vehicular routes within the Mojave Desert.							
Route types[1]	Spatial scales[2]	Plant communities[3]	Ecosystem response variables[4]				Citation
			Soils	Annual plants	Perennial plants	Animals	
OHV	Direct	Creosotebush Scrub	Soil strength, compaction, soil water at 30 cm.	Cover, density	NE	NE	Adams et al. 1982a,b
OHV	Direct Indi-rect	Creosotebush Scrub	NE	NE	Cover, density	NE	Artz 1989
OHV	Direct	Joshua Tree Woodland and Creosotebush Scrub	Soil crust cover, soil tex-ture, and nitrogenase activity	NE	NE	NE	Belnap 2002
OHV	Direct Indi-rect	Creosotebush Scrub	NE	NE	NE	Mortality of small terres-trial verte-brates, desert tortoise	Brattstrom and Bond-ello 1983
OHV	Direct	Creosotebush Scrub	NE	NE	Seedling ger-mination and survival. Myc-orrhizae development.	NE	Brum et al 1983
OHV	Direct	Creosotebush Scrub	NE	NE	Density	Desert tor-toise density relative abun-dance and live weight	Bury 1987 (bulletin)
OHV	Direct	Creosotebush Scrub, Desert Psammophytic Scrub, Shad-scale scrub	NE	Density, vol-ume, species composition	Cover, den-sity, volume, species com-position	Density, bio-mass and species com-position of invertebrates, reptiles and rodents.	Bury and Lucken-bach 1983

OHV	Direct Dispersed	Creosotebush Scrub	NE	NE	Cover, density	Desert tortoise abundance, density, biomass and habitat	Bury and Luckenbach 2002
OHV	Direct Dispersed	Creosotebush Scrub	NE	NE	NE	Lizard density and biomass	Busack and Bury 1974
OHV	Direct	Creosotebush Scrub	Compaction, bulk density	Density, species composition	Cover, species composition	NE	Davidson and Fox 1974
OHV	Direct	Creosotebush Scrub	Total suspended particulate size and volume. Soil texture and soil moisture	NE	NE	NE	Dyck and Stukel 1979
OHV	Direct	Not specific to a vegetation type	Desert pavement	NE	NE	NE	Elvidge and Iverson 1983
OHV	Direct	Creosotebush Scrub	Compaction, bulk density	NE	NE	NE	Fox 1973
OHV	Direct	Not specific to a vegetation type	Erosion, runoff, sediment yield	NE	NE	NE	Hinckley et al. 1983
OHV	Direct	Creosotebush Scrub	Erosion, sediment yield	NE	NE	NE	Iverson 1980
OHV	Direct	Creosotebush Scrub	NE	NE	Cover, density	NE	Lathrop 1978
OHV	Direct	Creosotebush Scrub, Desert Psammophytic Scrub, Shadscale scrub	NE	Cover related to motorcycle track density and depth	Cover, density, diversity,	NE	Lathrop 1983a
OHV	Direct	Creosotebush Scrub	NE	NE	Cover, density, productivity, diversity (species richness/species evenness) and stability expressed as CQI	NE	Lathrop 1983b

OHV	Direct	Blackbrush scrub	bulk density, compaction, pore space	NE	NE	NE	Lei 2004
OHV	Direct	Creosotebush Scrub, Desert Psammophytic Scrub, Shad-scale scrub, Desert Micro-phyll woodland	NE	Density (10m x 10m)	Cover, den-sity, volume.	Density, spe-cies richness, biomass of reptiles and mammals.	Lucken-bach and Bury 1983
OHV	Direct	Creosotebush Scrub	Soil texture, particle size, bulk density, soil moisture, penetration resistance, infiltration rate,	NE	Cover, germi-nation of transplanted seedlings.	NE	Marble 1985
OHV	Direct	Creosotebush Scrub	Compaction, soil moisture, soil texture, penetrometer, infiltrometer	NE	Cover, density	NE	McCarthy 1996
OHV	Direct	Creosotebush Scrub (Colo-rado Desert)	NE	NE	NE	Flat-tailed horned lizard biomass, rates of move-ment, and activity areas as affected by an OHV race.	Nicolai and Lovich 2000
OHV	Direct	Creosotebush Scrub, Salt Bush Scrub, Desert Psam-mophytic Scrub	NE	species rich-ness, repro-duction	species rich-ness, repro-duction	NE	Pavlik 1979
OHV	Direct	Creosotebush Scrub	soil compac-tion, bulk den-sity	NE	Cover and density. Spe-cies catego-rized as long lived or short lived	NE	Prose et al. 1987

OHV	Direct	Creosotebush Scrub	Compaction, bulk density, soil moisture, runoff, erosion and sediment yield	Cover	Cover	NE	Snyder et al. 1976
OHV	Direct	Creosotebush Scrub	soil compaction, texture, moisture.	NE	NE	NE	Tullock 1983
OHV	Direct	Shadescale Scrub	NE	Density	Density	Mark and recapture census of rodents and lizards. Density, abundance and biomass.	Vollmer et al. 1976
OHV	Direct	Creosotebush Scrub	Compaction, infiltration	NE	NE	NE	Webb 1980
OHV	Direct	Creosotebush Scrub, Shadscale Scrub	Compaction, penetration depth and resistance, bulk density and shear stress.	NE	NE	NE	Webb 1983
OHV	Direct	Not specific to a vegetation type	Soil Compaction	NE	Cover, density	NE	Webb, Wilshire and Henry 1983
OHV	Direct	Not specific to a vegetation type	Microfloral elements, inorganic elements	NE	NE	NE	Wilshire 1983
OHV	Direct	Creosotebush Scrub	Compaction	NE	NE	NE	Wilshire and Nakata 1976
OHV, ILR	Direct	Creosotebush Scrub	Nutrient levels, bulk density, soil moisture, pH compaction, total N, N pool, N mineralization, available P.	NE	Cover, density, volume, species composition	NE	Bolling and Walker 2000

OHV, ULR, ILR	Dispersed	Creosotebush Scrub, Black-brush Scrub	NE	Cover, seed-bank density, diversity	Cover, diver-sity	NE	Brooks et al. in prep
ULR	Direct	Creosotebush Scrub, Shad-scale Scrub	Compaction, bulk density, soil moisture, soil texture	NE	Cover, den-sity and spe-cies composition	NE	Webb and Wilshire 1980
ULR	Direct	Creosotebush Scrub, Shad-scale Scrub	NE	NE	Density, Fre-quency	NE	Wells 1961
ULR, ILR	Direct	Creosotebush Scrub	Nutrient lev-els, bulk den-sity, soil moisture, pH compaction, total N, N pool, N miner-alization, available P.	NE	Cover, den-sity, volume, species com-position	NE	Bolling 1996
ULR, ILR	Direct Dis-persed	Creosotebush Scrub	Total soil Nitrogen	Species rich-ness, biom-ass, density	Cover, spe-cies richness	NE	Brooks and Berry accepted
ULR, ILR	Direct	Creosotebush Scrub, Salt Bush Scrub	NE	NE	Cover, den-sity, abun-dance. Perennials grouped as long lived and short lived (Vasek et al. 1975). Transects were then compared with a Com-munity Qual-ity Index.	NE	Vasek et al. 1975
ILR	Direct	Creosotebush Scrub	NE	NE	Cover, den-sity, biomass, richness	NE	Lathrop and Archi-bold 1980a
ILR	Direct	Creosotebush Scrub	NE	NE	Cover, den-sity, biomass, richness	NE	Lathrop and Archi-bold 1980b

ILR	Direct Indirect	Creosotebush Scrub, Salt Bush Scrub, Joshua Tree Woodland	NE	NE	Cover, density, species richness, abundance. Measurable road edge effect occurs only where there is a significant berm.	NE	Star and Mefford 2002
ILR	Direct Indirect	Creosotebush Scrub, Salt Bush Scrub, Joshua Tree Woodland	NE	NE	NE	Cover, density, diversity of antelope ground squirrel	Starr 2001
ILR	Direct	Creosotebush Scrub, Shadscale scrub	Water retention, bulk density, pH, texture, total nitrogen	NE	NE	NE	Walker and Powell 2001
AR	Direct	Creosotebush Scrub (Chihuahuan Desert)	NE	NE	Cover, biomass, volume, foliar nitrogen, foliar resin	Arthropod density, biomass.	Lightfoot and Whitford 1991
ILR, AR	Direct	Creosotebush Scrub	NE	density species composition. Highest density values of winter annuals along paved roadside.	Density cover biomass. Roadside productivity higher than non-roadside, with paved productivity greater than unpaved.	NE	Johnson et al. 1975
LAH	Direct,	Creosotebush Scrub, Shadscale Scrub	NE	NE	NE	Mortality of small terrestrial vertebrates, desert tortoise along a state highway in fenced and unfenced areas.	Boarman and Sazaki 1996

LAH	Direct, Dispersed	Creosotebush Scrub, Shadscale Scrub	NE	NE	NE	Mortality of small terrestrial vertebrates, desert tortoise along a state highway in fenced and unfenced areas.	Boarman, et al. 1997
LAH	Direct Indirect	Creosotebush Scrub	NE	NE	Percent cover	Abundance, species richness of rodents.	Garland and Bradley 1984

[1]OHV (OHV trails), ULR (unimproved local roads), ILR (improved local roads), CR (collector roads), AR (arterial roads), and LAH (limited-access highways)[2]direct, indirect, dispersed

[2]direct, indirect, dispersed

[3] Munz 1974

[4] NE = not evaluated